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Modelling of cryogenic cooling system design concepts for superconducting aircraft propulsion

Joseph Palmer, Essam Shehab ✉

Department of Manufacturing, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield MK43 0AL, Bedfordshire, UK

✉ *E-mail: e.shehab@cranfield.ac.uk*

Abstract: Distributed propulsion concepts are promising in terms of improved fuel burn, better aerodynamic performance, and greater control. Superconducting networks are being considered for their superior power density and efficiency. This study discusses the design of cryogenic cooling systems which are essential for normal operation of superconducting materials. This research project has identified six key requirements such as maintain temperature and low weight, with two critical components that dramatically affect mass identified as the heat exchanger and compressors. Qualitatively, the most viable concept for cryocooling was found to be the reverse-Brayton cycle (RBC) for its superior reliability and flexibility. Single- and two-stage reverse-Brayton systems were modelled, highlighting that double stage concepts are preferable in specific mass and future development terms in all cases except when using liquid hydrogen as the heat sink. Finally, the component-level design space was considered with the most critical components affecting mass being identified as the reverse-Brayton compressor and turbine.

1 Introduction

With aviation popularity increasing, stringent emissions targets are being outlined by aviation authorities [1, 2]. To achieve these targets, the aerospace industry is investigating more radical aircraft designs such as blended-wing body (BWB) [3].

Distributed propulsion is one novel method of aircraft propulsion being considered in detail. Distributed propulsion is a method of propulsion whereby multiple propulsors are linked [4]. This allows a host of advantages to be exploited, including higher overall bypass ratios and freedom of propulsor placement.

Electrically driven distributed propulsion [5] is focusing on light weight, efficient systems to maximise propulsion performance benefits. Superconductivity is being considered as an option to deliver these advantages. Superconductors have the ability to transfer large amounts of energy with no dc loss. Electrical machines could be made smaller and more efficient than conventional counterparts using superconductivity. The use of superconductivity requires cryogenic cooling.

This paper presents an innovative modelling approach for conceptual cryogenic cooling system design for a future aerospace superconducting electrical system.

2 Research context

National Aeronautics and Space Administration (NASA) is investigating a distributed propulsion solution known as N3-X. This aircraft features a BWB airframe, wing-tip mounted gas turbines, and 14 superconducting ducted fan propulsors mounted on the trailing edge of the body [6].

From an electrical perspective, the N3-X project is investigating two types of superconducting material that require different cooling conditions. The first is magnesium diboride (MgB_2), superconductor with a critical temperature (T_c) of 39 K [7]. The second is bismuth strontium calcium copper oxide (BSCCO) with a T_c of 110 K [8]. The aircraft assumes a fully superconducting network with a total installed maximum propulsion power rating of ~80 MW [9]. Predicted generator-to-propulsor losses for the N3-X are 0.03% for the fully superconducting concept. The estimated reduction in fuel burn for the concept is 72% for the liquid hydrogen (LH_2) cooled MgB_2 version and 70% for the BSCCO version when compared with the baseline aircraft, a Boeing 777-200 Long Range (LR) [9].

Use of a cryocooler for the N3-X is restricted to the BSCCO concept due to the exponential rise in required cryocooling power as temperature decreases. The primary assumption behind this is that the cryocooler will exchange heat with the ambient air, using air flow as the heat sink in order to remove loss inside the cryostat.

Project distributed electrical aerospace propulsion (DEAP) a collaborative project between Airbus Group Innovations, Rolls-Royce, and Cranfield University is also investigating superconducting propulsion systems for aircraft [10]. The focus is to deliver concept design tools that at this stage focus primarily on efficiency and weight trades.

The DEAP aircraft in contrast to the N3-X BWB airframe is a tube and wing configuration [4]. Distributed fans are located at the aft fuselage in order to re-energise the boundary layer [11]. The number of variables in the propulsion configuration however is higher, with number of propulsors and height of the boundary layer ingested being key variables in terms of configuration.

The DEAP electrical system is being investigated from both a conventional and superconducting perspective. The superconducting concept utilises MgB_2 components. The cryogenic cooling method needs to consider concepts from direct cooling using LH_2 to the use of a cryocooler in order to assess the viability of each concept.

This paper will present some of the results from the DEAP study from the cryogenic cooling system perspective, highlighting the challenges associated with high-powered aerospace cryogenics.

3 Problem definition and scope

Cryogenics is a well-established and understood field of science; however, the application of cryogenics to the specific problem of high-power superconducting networks is new. Superconducting machines are still only in their infancy in terms of practical use with some partially superconducting machines already in development [12]. At the time of writing however there is no known design process for fully superconducting machines, with practical examples existent in experimental form only. This statement is particularly relevant when considering the cryogenic cooling system, because it means that the magnitude of thermal losses in any future superconducting network is not fully understood. In addition, cryogenic cooling also requires a high-power demand itself. When considering the coefficient of performance (COP) for a cryocooler, the low temperatures necessary for superconductivity mean that considerably more power than is absorbed in the cryostat must be put into the system. When fixing the rejection temperature and cold power, the required input power with respect to temperature follows a rough inverse-square curve [13].

The first design trade-off challenge arises out of this statement when considering the performance of superconductors. A superconducting materials' current-carrying capability depends on three parameters: current density, magnetic field density, and temperature. For example, if the temperature for a given superconductor is lowered, the current density and magnetic density parameters improve leading to an improved electrical system. However, decreasing the temperature means that the cryogenic cooling system will have to work exponentially harder. This effect can be observed in N3-X study where the potential cryogenic plant weight is between 25 and 34% of the total propulsion system weight depending on whether BSCCO or MgB_2 is used [9]. From a design perspective, this means that the performance of the superconducting network will vary inversely to the performance of the cryogenic system.

The second challenge is the selection of an optimum method to deliver cryogenic cooling given the number of different methods of achieving cryogenic temperatures. Finally, it is necessary to bring these challenges together as part of the overall final DEAP concept configuration analysis to support the overall modelling toolset development.

4 Research methodology

The systems engineering design process was selected due to the number of variables and complexity of the task. This method begins by gathering requirements through the various stakeholders in the project. Following this the requirements are sorted into following categories:

- Operational requirements.
- Functional requirements.
- Non-functional requirements.
- Performance requirements.

Functional requirements are then selected for modelling. A functional model of the cryogenic cooling system is generated that models every other system that it interacts with.

Once a functional model is generated, the next steps are to perform analysis on the model in order to understand which functional requirements are most critical. This process uses three methods: sensitivity matrix, failure modes and effects analysis (FMEA), and quality function deployment (QFD).

On the basis of the critical functions, the concept selection process can be performed. This is achieved by the use of function means analysis (FMA) supported by Simulink modelling to assess which components within the concept drive the trade factors (efficiency and weight).

The conclusion of this paper analyses the results of the FMA and associated modelling work, with discussion on the successes of the approach used and on potential improvements for future iterations. The research implications and future work are also discussed briefly.

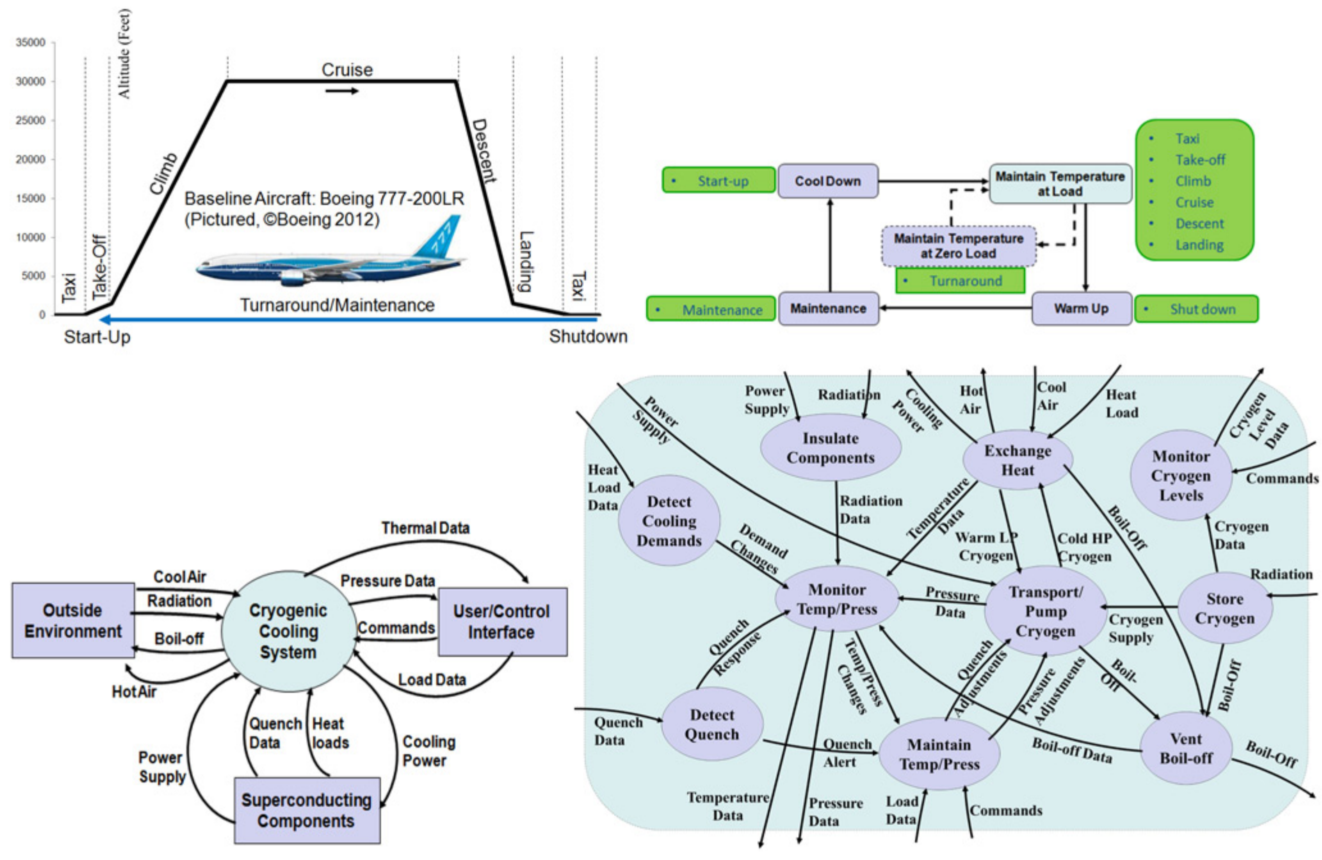

Fig. 1 *Operational functional modelling*

a, b Mission profile and cryogenic cooling system modes of operations diagram with corresponding mission segments
c System level functional flow diagram showing inputs and outputs
d Sub-system level functional flow diagrams showing management of inputs and outputs

5 Stakeholder analysis and requirements capture

A stakeholders list was compiled. The stakeholders were then ranked according to their involvement in the project at the conceptual design stage. The most relevant stakeholders were deemed to be:

- Conceptual electrical engineers.
- Conceptual aerospace engineers.
- Electrical design engineers.

Conceptual electrical engineers were deemed critical for their knowledge on superconducting systems. Without prior knowledge of these systems, the purpose of the cryogenic cooling system cannot be fully understood. Conceptual aerospace engineers are also highly relevant at this stage for airframe knowledge and eventual potential implementation. The aircraft itself will present challenges to the design of the cryogenic cooling system such as weight and space restrictions; therefore, it is important to understand the level of potential improvement current cryogenic cooling system will require in order being viable. Electrical design engineers play a crucial role in understanding the practicalities of electrical networks on aircraft.

To ensure no individual bias, two engineers from each group of stakeholders were interviewed, six in total, each with different levels of seniority. This ensures a ‘top-down, bottom-up’ perspective on requirements, which ensures a broad view of how the cryogenic system is perceived by stakeholders. The interview process first focuses on generation of requirements that fits within six key performance indicators. The groups were:

- Good efficiency.
- Good control.
- Good performance.
- Safe operation.
- Easy integration.
- Long life.

Following the generation of a full set of requirements, each stakeholder ranked the set from 1 to 5, with 1 representing least critical and 5 the most critical. In addition, the stakeholders selected their key critical requirement from each group resulting in the following initial set of key requirements:

- Maintain temperature.
- High reliability.
- Airframe compatibility.
- Shock endurance.
- Low weight.

6 Functional modelling and analysis

To support functional modelling, a mission profile is selected to understand the operational scenarios the cryogenic system must be designed for. This process has previously been outlined [14]. The operational modes are shown in Figs. 1*a* and *b*.

The mission profile selected is based on the same baseline aircraft as used within the N3-X project. The mission profile is simplified into distinct segments, based on the differences in propulsion power levels required. Segments such as loiter are similar in nature to cruise and descent, hence they are omitted. The segments are then associated to the cryogenic cooling system operational mode they relate to, and the mode with the most associated segments is deemed most critical. This highlights the critical operational mode as ‘Maintain Temperature at Load’. If the cryogenic cooling system cannot satisfy the minimum requirements within the critical mode, the concept is dropped.

To understand which inputs and outputs are necessary for operation of the cryogenic system, the outside systems with which it interacts must be determined. This is done in two stages: the super-system level and the sub-system level. Fig. 1*c* shows the interactions between the systems. This is still kept generic by including cooling air and boil-off, in case of eventual adoption of either ambient air heat sink or LH_2 heat sink.

Three other systems have been identified as vital to normal operation. Once each system and its relative inputs and outputs are determined, the cryogenic cooling system functions can be plotted within the functional model at the sub-system level shown in Fig. 1*d*. The originally generated functional requirements are used initially, and the functional flows of inputs and outputs are hypothetically considered. If a function is deemed to be missing, it is added to the model so the unassigned input/output is handled correctly. Additionally, if any single function is deemed to be overloaded or excessively complex, that function can be divided into multiple functions. For example, quench detection could be performed through the ‘Monitor Temp./Press.’ function. When considering the implications of a superconducting system quench event, to prevent damage to the system due to thermal shock or sudden coolant pressure rise, it is necessary to have a separate function that can respond rapidly and independently of other functions.

After three iterations of the model, it can be tested in order to identify the key functions. This is performed in three stages: sensitivity analysis, FMEA, and QFD. Sensitivity analysis begins by plotting each input against each output and recording the sensitivity of the outputs when the inputs are varied. The inputs are considered in two modes: double input level and zero input level. For example, if the cold air input stops, the hypothetical impact on each corresponding output is recorded. Functions of high sensitivity can be identified early on, and close attention paid to concepts that satisfy these areas of sensitivity.

FMEA analysis involves considering hypothetical situations within the cryogenic cooling system representing events that may occur and the effects they may have. This is done at the conceptual level and the functional level. For example, a variable may include loss of vacuum within the ‘Insulate Components’ function. The impact on the whole system is then considered, and assigned a severity factor, risk of occurrence factor, and ease of detection factor, all between 1 and 10. These are then multiplied to give a risk priority number, which indicates how serious a fault in any given scenario will be.

QFD analysis assesses the original requirements and their critical rankings against the functions generated, whereby the relationships of each function to each requirement is recorded. If there is a strong relationship, a 9 is assigned, which is then multiplied by the criticality factor of the requirement. For medium and weak relationships, a 3 or 1 is assigned. If there is no relationship, the space is left blank. The totals for each function are then added, giving the most critical functions.

Table 1 shows the results of the analysis, with the total highlighting the most critical functions. Five functions have been identified as critical where a value of 9 or higher is deemed to be of critical importance. The critical functions are:

- Detect cooling demands.
- Exchange heat.
- Transport/pump cryogen.
- Store cryogen.
- Vent boil-off.

Table 1 Results from functional model analysis (levels range from 1 to 5, with 1 being least critical and 5 being most critical)

Function	Sensitivity analysis	FMEA	QFD	Total
detect cooling demands	4	4	3	11
detect quench	3	2	3	8
insulate components	3	2	3	8
monitor temp./press.	4	1	3	8
exchange heat	5	1	4	10
maintain temp./press.	5	1	2	8
transport/pump cryogen	5	1	5	11
monitor cryogen levels	4	1	3	8
store cryogen	4	1	4	9
vent boil-off	5	3	4	12

7 Concept selection

The next step is to consider techniques to deliver the critical functions. The first step is to use FMA. Functions are plotted on a spreadsheet, and known ways of achieving those functions are listed alongside it. Once all known possible ways are collected, the functions are assessed in three stages. The first is plausibility; outlandish or unrealistic concepts are ruled out. The second is qualitative; the known qualities of each concept are considered, and a judgement is made on which concepts can be ruled out after basic investigation of qualities. Finally, a thorough quantitative assessment is performed on the remaining concepts, to detect which is the most viable.

Functions which most affect the DEAP trades are crucial. Though deemed a critical function, 'Detect Cooling Demands' will not impact weight or efficiency of the system hence it is ignored. Similarly, 'Vent-boil-off' is also not considered. The store cryogen function is also omitted. The reason is that for a closed-loop cryocooler, the storage of the closed-loop fluid is insignificant in comparison with the cryocooler itself whilst an open-loop system is out of scope of DEAP concept where kerosene fuel is assumed.

Previous studies have been completed on the viability of different cryocoolers for this application [14]. Two main types of cryocooler exist: regenerative and recuperative. Regenerative cryocoolers rely on reciprocating flow of cryogen through a regenerative matrix material where thermal energy is stored. Examples of this are stirling cycle, pulse tube (PT), and Gifford McMahon (GM). PT and GM rely on an external compressor which is often bulky and heavy. Previous studies have indicated that when considering potential future cryocooler development even an 80% reduction in weight by 2035 would still not be sufficient. Recuperative cryocoolers rely on a continual flow of unidirectional fluid which exchanges thermal energy through heat exchangers rather than a regenerative matrix. There are advantages to using recuperative cryocoolers such as the ability to have high mass flow rates, reducing cool down and thermal transient response times. A key example of recuperative cooling is the reverse-Brayton cycle.

The reverse-Brayton cycle cryocooler (RBCC) is considered the most viable option. RBCCs are already in use within aerospace applications on small power scales, and have exhibited high reliability and efficiency, with some examples reaching 50,000 h of maintenance-free operation [15]. RBCC in its basic form consists of a compressor, turbine, and a hot and cold heat exchanger. On qualitative terms, the cold heat exchanger can effectively be eliminated as a result of the application; superconducting machines and cables can be sufficiently designed to act as heat exchangers through which cold fluid is pumped. High reliability coupled with lower mass for a given application makes RBCC the cryocooler of choice for high-power aerospace applications. NASA studies have also confirmed this choice assuming a two-stage RBCC for their N3-X concept [16].

Project DEAP has not defined the cryogenic cooling system; rather the results of this paper's modelling work will explore the design space to determine which configuration of RBCC is best.

8 Model assumptions

Two models are constructed: a single-stage RBCC and a two-stage RBCC. A number of assumptions are made in order to model the system without unnecessary complexity at this early stage:

- No cryogen transport losses.
- No bearing losses.
- Closed system apart from heat sink and cold heat exchange.
- The motor used is superconducting for compression.

Brayton systems are well understood from a numerical performance perspective [17]. However, determining how the weight of an RBCC system varies with power is a primary objective. NASA has previously performed a study on Brayton power systems for space applications [18]. The study outlines a method for predicting the mass of future concept designs of Brayton power systems by plotting the input power specific mass against the shaft input power of the system for known examples. Since the method applies to aerospace designs and to single-stage Brayton power systems, the assumption of correlation can also be made when considering RBCC. At a component level, Brayton power systems are no different to RBCC; the key difference between them is that an RBCC removes heat and requires input power, whereas Brayton power systems uses heat to generate power.

Table 2 List of RBCC cryocoolers found with known masses, input powers, and their respective practical applications

RBCC type	Input power, kW	Specific mass, kg/kW
aerospace	3	7.333
industrial	0.2	77.500
aerospace	0.16	68.750
aerospace	0.26	42.308
aerospace	21	12.857
aerospace	0.4	52.500
industrial	1000	8.000

The first step to weight estimation is to collect weight data of known RBCC. Since each system is custom made and no known commercial off-the-shelf designs exist, both industrial and aerospace RBCC are included in this paper. Table 2 shows data collected for seven cryocoolers whose mass and input power could be determined. Owing to the low number of data points, the mass estimation curve must be scrutinised to determine whether the curve represents an acceptable level of accuracy for this paper.

The data collected shows a similar inverse-square type curve to that shown in the NASA Brayton power systems study previously mentioned [18]. The relationship in Fig. 2 shows the curve fit for the cryocooler data, with the relationship shown in (1)

$$m_{\mathrm{RBCC}} = 27.5 P_{\mathrm{input}}\, \mathrm{e}^{-1.225\left(\log_{10} P_{\mathrm{input}}\right)} \tag{1}$$

where m_{RBCC} is the weight of the cryocooler and P_{input} is the cryocooler input power in kilowatts. The regression analysis shows an adjusted R^2 value of 0.855. Given the data is dispersed particularly within the x-axis, it is necessary to discuss the data points. At the top of the curve, the cryocoolers are small, aerospace cryocoolers with one older industrial design.

The relationship described by (1) must be scrutinised in order to establish whether it can be used to provide valid mass estimation for this project. The applications considered by this paper will focus on higher-power cryocoolers; hence, the most critical region on the relationship shown in Fig. 2 will be input powers higher than 10 kW since this is the minimum cold load expected.

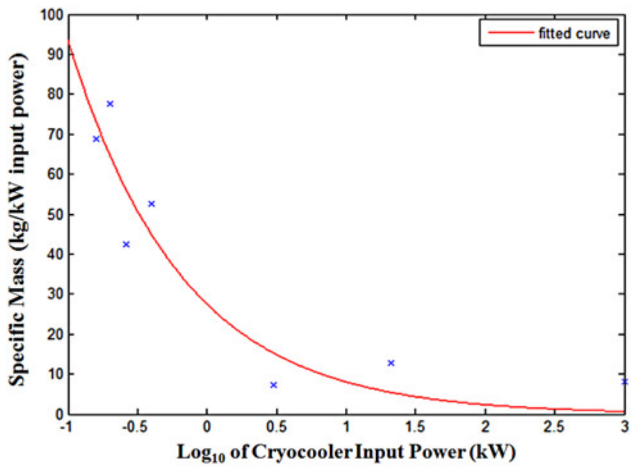

Fig. 2 *Relationship between specific mass and $\log_{10}$ of input power for known RBCC*

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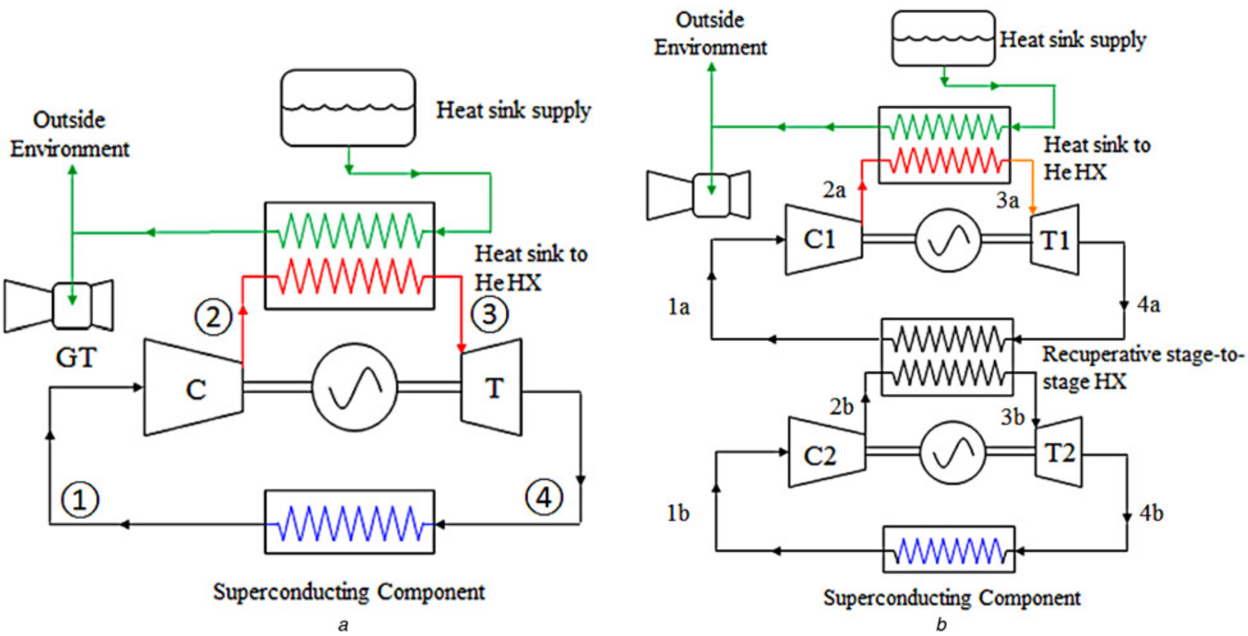

Fig. 3 *Model development*

a Schematic diagram of a basic single-stage RBCC with an open-loop heat sink
b Schematic diagram of an open-loop heat sink basic two-stage RBCC

Two data points on the graph are of particular interest: the industrial 1 MW input power design and the 3 kW input power aerospace design. The specific masses are similar despite the larger 1 MW cryocooler being over two orders of magnitude larger in terms of input power than the aerospace 3 kW design. This shows the significant available mass optimisation potential between aerospace and industrial designs.

Studies have indicated that industrial cryocoolers could save 80% or more mass when simply replacing industrial materials such as steel with aerospace grade materials [19]. A brief numerical comparison was carried out on the mass estimation method by using known single and multi-stage RBCC examples. The analysis performed used values of input power and compared the actual masses against the relationship-generated mass values. The relationship described in (1) was found to have a mean mass estimation accuracy of ±15.4%, with accuracy increasing for high-power examples above 10 kW input power, and decreasing for low-power examples of <1 kW input power. Given the potential future technological advancements and the conceptual nature of this paper for 2035 aircraft [20], an uncertainty factor of <20% is acceptable [10].

9 Model development

Fig. 3*a* shows the schematic overview for the single-stage model, developed using the relationships outlined by Swift [17] and described below. Single-stage RBCCs are typically only used for smaller temperature differentials between cold and hot heat exchangers.

The single-stage RBC parametric flow to obtain the required input power of the cryocooler is essential. The basic flow is described as follows. Parameters are taken from the cold heat exchanger initially and fed back through the turbine, heat sink heat exchanger, and compressor. Initially a mass flow rate $\dot{m}$ is calculated using the superconducting cold loads of the network and cryocooler motor, $\dot{Q}_{\text{cold}}$ and $\dot{Q}_{\text{m}}$, respectively

$$\dot{m} = \frac{\dot{Q}_{\text{cold}} + \dot{Q}_{\text{m}}}{C_{\text{p}} \Delta T_{4-1}}$$

Pressure is calculated using the defined pressure drop and ambient pressure at point 1 in the RBC cycle. Since pressure is known, the turbine pressure ratio can be determined as T_3 and is defined as the heat sink input temperature. The term ΔT_{4-1} represents the change in temperature over the cold heat exchanger and C_{p} is the specific heat capacity at constant pressure for helium

$$P_3 = P_4 \cdot \left(\frac{T_3}{T_4}\right)^{\left(\frac{1}{\eta_{\text{pct}}} \frac{\gamma}{\gamma - 1}\right)}$$

where γ represents the ratio of specific heats for helium and η_{pct} is the turbine polytropic efficiency. Turbine energy recovery can be calculated since all required parameters are now known

$$\dot{Q}_{\text{t}} = \dot{m} C_{\text{p}} \Delta T_{3-4}$$

The pressure drop over the warm heat exchanger (ΔP_{Hxw}) is a defined input variable, and is used with the turbine inlet pressure P_3 to determine the compressor outlet pressure P_2

$$P_2 = \frac{P_3}{1 - \Delta P_{\text{Hxw}}}$$

Since the compressor pressure ratio is now known, the compressor temperature ratio can be calculated using the compressor polytropic efficiency, η_{pcc}

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma - 1}{\gamma \eta_{\text{pcc}}}\right)}$$

From knowing the compressor temperature ratio, the required compressor input energy $\dot{Q}_{\text{c}}$ can be calculated since mass flow is conserved and all other information are known

$$\dot{Q}_{\text{c}} = \dot{m} C_{\text{p}} \Delta T_{2-1}$$

Finally, the total energy required to drive the system at steady-state conditions is given by subtracting the turbine energy recovery from the compressor required input power

$$\dot{Q}_{\text{input}} = \dot{Q}_{\text{c}} - \dot{Q}_{\text{t}}$$

The efficiency is calculated as below

$$\eta_{\text{RBC}} = \frac{\dot{Q}_{\text{cold}} + \dot{Q}_{\text{m}}}{\dot{Q}_{\text{input}}}$$

Fig. 3*b* shows the schematic overview for the two-stage model, again derived using relationships outlined by Swift [17]. Two-stage RBCC's are commonly used when the temperature differential between the heat sink and cooled component is higher. Modelling two-stage systems is somewhat more complex than with single-stage RBCC. Complexity arises from the intermediate stage heat exchanger. A method for determining the temperature at which the exchange must take place is necessary. The method developed during this paper creates an equal turbine temperature ratio share. Equation (2) shows the method

$$\frac{T_{3b}}{T_{4b}} = \sqrt{\frac{T_{3a}}{T_{4b}}} \tag{2}$$

Here, a represents the warm stage and b represents the cold stage. Since the turbine inlet for the cold stage, T_{3b} is unknown, the turbine outlet temperature for the cold stage T_{4b} (defined by the desired cold temperature) can be used alongside the warm stage turbine inlet temperature T_{3a} in order to give an overall system turbine temperature ratio. The square root gives the turbine temperature ratio that ensures each stage is running at the optimum equal COP. Modelling work assumes for a two-stage design that the components for each stage such as compressor and turbine are equally efficient. To prevent either the hot or cold stages from efficiency restriction when considering the Carnot efficiency, the COP for each stage must also be equal.

At a component level for modelling purposes, the compressor is assumed to be dynamic rather than fixed displacement. The key reason is mass flow. Heat exchanger performance can be increased by increasing mass flow of the cryogenic fluid. Normally, this would create high-pressure losses in the system; however, due to the low molecular mass of the working fluid helium this is less of a concern. With modern day aerospace heat exchangers such as those being tested by Reaction Engines Ltd. [21], the assumption of using dynamic compression technology is reinforced. A second reason is that fixed displacement compressors are not included in the weight estimation survey.

There are three heat sinks considered in this paper; ambient air at 300 K, liquid methane (LCH_4) at 110 K, and LH_2 at 20 K. The heat sink within the model acts only as a coolant temperature to determine the most effective configuration based on heat sink. Different temperatures are also explored within the superconducting components, with a maximum inlet temperature of 20 K and a minimum temperature of 10 K. This fits within the optimum critical temperature range for MgB_2. Two-stage RBCC are not considered for use with LH_2 as a heat sink since the temperature differential between the cold and hot heat exchangers is sufficiently small already. Furthermore, for the purposes of this analysis, the intermediate heat exchanger is assumed to be ideal, whereby there is no temperature differential between the a and b stage fluid flows either side of the intermediate heat exchanger. The reason for this assumption is that component-level inefficiency in terms of pressure must first be assessed before investigating further component-level detail. Pressure has been identified as a critical parameter in the previous qualitative analysis, and must be given precedence over incidental component-level efficiencies to enable confirmation that the research methods for both quantitative and qualitative are consistent.

10 Modelling results and discussion – superconductor and heat sink temperature

The modelling results are split into three analyses. The first is to determine the sensitivity of the input power and mass of single- and two-stage RBCCs for the DEAP project concept. The assumptions and power level of 10 kW are used arbitrarily, in order to represent the order of magnitude of losses outlined in Project DEAP, along with the 10–20 K desired superconductor temperature for MgB_2. The second analysis is aimed at the N3-X concept investigating the relationship between heat sink temperature and specific mass. The assumptions of 65 K BSCCO operating temperature is used as with the N3-X cryocooled concept; however, the use of LCH_4 is also included within the heat sink temperature range in order to determine at which point the concept meets the 3 kg/kW specific mass target previously outlined [9]. In all cases where cryocooler mass or cryocooler specific mass is mentioned, this figure includes the component masses (compressors, turbines, heat exchangers, motors), but not the fluid masses required to cool (LCH_4, LH_2, and air). The 12 kW cold load used for the analysis is as outlined within the N3-X previous work [9]. Finally, the component-level efficiencies are plotted for single- and two-stage concepts using the DEAP assumptions. The overall impact on the DEAP aircraft concept fuel burn for pessimistic and optimistic cryogenic system assumptions is discussed. The simulations ran at fixed cold load for the variables outlined whilst all other variables such as heat exchanger temperature differential ($T_2 - T_3$, or heat exchanger inlet temperature minus heat exchanger outlet temperature) are fixed.

Table 3 describes the model input parameter assumptions used for this paper. Assumptions were made through interviews with experts around practical aspects of superconducting component operations and cryogenics. Model parameters in both single- and two-stage models are handled in reverse; cold component inputs are fed into the turbine model block, which are then fed back through the heat sink heat exchanger and finally the compressor block. The input

Table 3 Parametric assumptions for the RBCC single- and two-stage models where variables are not used

Model input parameters	Parametric model assumptions
cold heat exchanger ΔT, K	10; any higher-end performance of the superconductor is negatively impacted
heat sink heat exchanger ΔT, K	from compressor outlet temperature (T_2) down to heat sink inlet temperature (latent heat capacity considered)
helium specific heat, C_p, kJ/kg K	5.2; assumed constant over the range of temperatures in this paper
helium ratio of specific heats	1.66; constant over the temperature range
compressor polytropic efficiency, %	75% (pessimistic; based on present day technology) 85% (realistic; based on best industrial compressors) 90% (optimistic; based on best aerospace compressors)
turbine polytropic efficiency, %	2% better than corresponding compressor in all cases
ambient helium pressure, Bar	2; this was selected as an arbitrary value for pressure ratio derivation
superconductor temperature, K	20 K for MgB_2 concepts 65 K for BSCCO concepts
heat exchanger pressure drop, %	5% (optimistic, based on low transport and turbulence loss) 10% (realistic, based on medium transport loss and turbulence) 15% (pessimistic, based on high transport loss and turbulence)

power is calculated by subtracting the turbine power recovery from the compressor input required.

Fig. 4*a* shows the relationship for both single- and two-stage RBCC concepts between the desired superconductor operating temperature and the cryocooler efficiency for each heat sink. All other input parameters in the model were fixed. The graph highlights how much of an impact the temperatures of the superconductor and heat sink have on the performance of the cryocooler. Single-stage RBCC with LH_2 heat sink clearly shows the most sensitivity to superconductor temperature. The single-stage RBCC using air as a heat sink has an overall efficiency between 0.39 and 0.82%, making the concept prohibitive for MgB_2 superconductors. Two-stage RBCC are slightly less efficient when considering the LCH_4 heat sink than single-stage designs, showing an efficiency of between 1.9 and 4.1%. Future superconducting concepts need to be resilient to sudden temperature changes hence the superconducting operating temperature sensitivity is crucial to practical applications. Fig. 4*a* highlights this extreme sensitivity to even small superconductor temperature changes, as the efficiency in all cases drops by over 50% of the original value.

When considering the use of LCH_4 as a heat sink, the single-stage concept still exhibits high sensitivity toward superconducting operating temperature with efficiencies between 1.9 and 4.1%. The two-stage LCH_4 series shows slightly lower overall efficiencies than with the single-stage. This small decrease in efficiency between the single- and two-stage designs can be attributed to the additional component losses experienced through having two component sets. Finally, the LH_2 concept for a single-stage RBCC is considered. Smaller single-stage RBCC could be used not only to provide direct cooling to components, but also to lower the temperature to 10 K from the 20 K LH_2 coolant, increasing the performance of the superconducting network. Owing to the high Carnot efficiency, overall efficiencies in this case are shown to be between 17 and 53%.

Fig. 4*b* shows the relationship between the superconductor temperature and mass for each concept. Since the mass is intrinsically linked to the input power, both the sensitivity of each concept to superconducting component and heat sink temperature is reflected. It is worthy of note that within Fig. 4*b* is the relative masses between the single- and two-stage concepts. Whilst the efficiency is only marginally smaller for two-stage concepts over single-stage concepts, the masses are significantly varied, with two-stage designs showing a large mass increase. A clear distinction can be made between single- and two-stage concepts in terms of mass. However, this is not representative of feasibility since single-stage concepts will certainly require larger pressure ratio, and therefore multiple compressor stages in order to achieve the desired performance. Compressors will have to be much larger per unit temperature differential between hot and cold heat exchangers; hence, the accuracy of the mass estimation at these high pressure ratios will need further investigation. Multiple compressor stages will be necessary which may further reduce the suitability of the mass estimation method. Fig. 4*b* shows that a two-stage design is slightly worst than a single stage for heat sinks except in the case of LH_2.

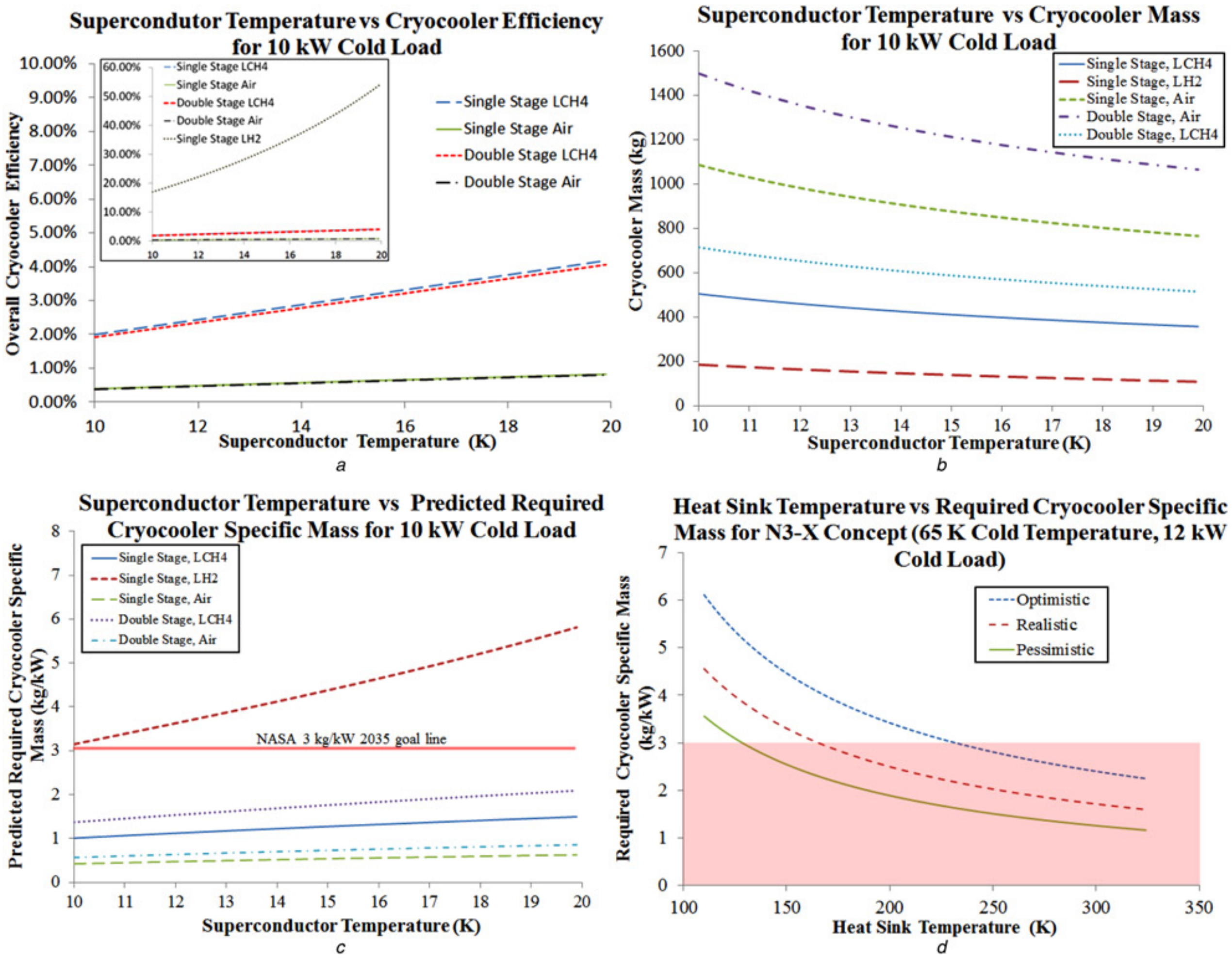

Fig. 4 *Superconductor and heat sink temperature impacts on power and mass for single and two-stage RBCC concepts*

a Superconducting operating temperature against cryocooler overall efficiency for 10 kW MgB_2 cryogenic load
b Superconducting operating temperature against cryocooler mass for 10 kW MgB_2 cryogenic load
c Cryocooler specific mass against superconductor temperature for 10 kW MgB_2 cryogenic load alongside NASA's 3 kg/kW target line
d Variation in specific mass of a two-stage RBCC with heat sink temperature, for optimistic, realistic, and pessimistic cases for N3-X

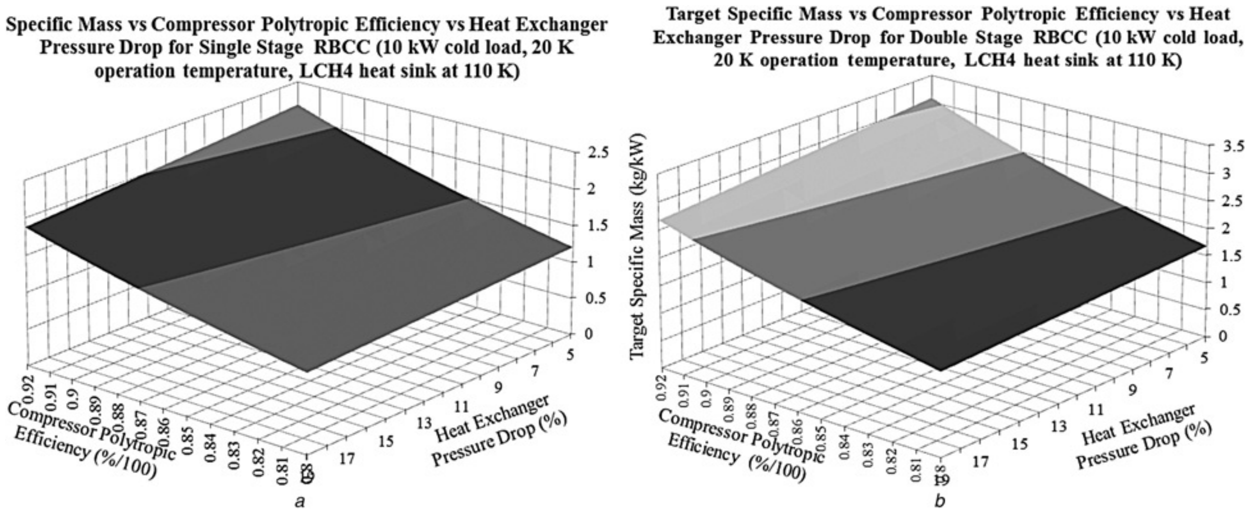

Fig. 5 *Modelling results and discussion – component efficiency*

a Specific mass sensitivity to heat exchanger pressure drop and compressor polytropic efficiency for single-stage RBCC
b Specific mass sensitivity to heat exchanger pressure drop and compressor polytropic efficiency for two-stage RBCC

Fig. 4*c* shows the variation of the cryocooler specific mass with superconductor temperature. Shown on the graph is the NASA target of 3 kg/kW input power deemed achievable. The graph shows that the single-stage LH_2 and two-stage LCH_4 can be realistically achieved when considering the load conditions and temperatures required for normal operation of MgB_2. All concepts using air and the single-stage LCH_4 concept are unachievable or require significant development. Fig. 4*c* also shows that the sensitivity of the single-stage LH_2 concept to the superconducting operating temperature is high as in Fig. 4*a*, with a 10 K temperature change representing nearly a 100% change in required cryocooler specific mass.

In the case of the N3-X concept, the model assumptions differ slightly. The superconducting component temperature is fixed at 65 K and the cold load is increased from 10 to 12 kW. The increase in load reflects the 24 kW overall cryogenic cooling load predicted, with the assumption that two cryocoolers are used for redundancy. Fig. 4*d* shows the relationship between heat sink temperature and the predicted required specific mass of the concept cryocooler. The cryocooler concept is a two-stage design similar to that outlined in the N3-X study.

The three different cases shown in Fig. 4*d* represent different levels of optimism for the component-level design. Fig. 4*d* shows that for LCH_4 temperatures pessimistic technology can meet the 3 kg/kW target outlined by NASA. As heat sink temperature increases toward the maximum ambient air temperature of 325 K, the 3 kg/kW goal begins to look more difficult to achieve and will require significant development in heat exchanger and compressor technology. This highlights the requirement for further component-level technological development when considering air as a heat sink for this application.

11 Modelling results and discussion – component efficiency

The final analysis in this paper focuses on the sensitivity of specific mass to component efficiency with regard to the DEAP concept for both single- and two-stage RBCC. The results of the input power and mass estimation in Figs. 5*a* and *b* show that the two-stage RBCC is preferable in cases not involving LH_2 as a heat sink when considering MgB_2 operational temperatures due to its potential for improvement. However, since LH_2 has wider storage and implementation issues, the most likely heat sink is LCH_4. Assuming a sink temperature of 110 K and an operating network temperature of 20 K, the difference between single- and two-stage systems in terms of specific mass is not significant. Therefore, it is necessary to understand how component-level performance affects the overall performance.

Fig. 5*a* shows how the single-stage concept specific mass varies when adjusting the pressure drop in each heat exchanger and the compressor and turbine polytropic efficiency. The turbine polytropic efficiency is assumed to be 2% better than the compressor in each data point. The graph shows that the range of values for the single stage does not meet NASA's 3 kg/kW goal, despite the optimism at the higher end of the plot. This suggests that while Fig. 4*b* shows that the single-stage concept for DEAP is more sensitive to temperature than the two-stage, the specific mass for the single stage is not greatly affected by improvements in component-level efficiency.

Fig. 5*b* showing the two-stage concept illustrates through the number of contours crossed that optimisation of components can result in significant gains in the required specific mass. Whilst in Fig. 5*a* the differential in specific mass from the least efficient to the most is 1.3 kg/kW, the two-stage exhibits gains of 1.8 kg/kW. This gain leads to the clear conclusion that two-stage concepts are more viable, both in numerical terms and in development potential for a given set of parameters. Furthermore, from both Figs. 5*a* and *b* it can be seen that the specific mass is comparatively insensitive to the pressure drop in heat exchangers. Fig. 5*a* shows a 14% pressure drop differential from 5 to 19% resulting in an overall likely specific mass gain of 0.5 and 0.2 kg/kW for the highest and lowest compressor polytropic efficiency values, respectively.

Fig. 5*b* shows that the two-stage concept specific mass is highly sensitive to the compressor efficiency. The graph shows a specific mass difference of 1.2 kg/kW for the lowest pressure drop value across the compressor polytropic efficiency range, whereas the highest pressure drop value suggests a specific mass difference of 1.5 kg/kW across the same range of compressor polytropic efficiency values. Fig. 5*a* showing the single stage also shows that when considering the difference in specific mass across the range of compressor polytropic efficiencies that pressure loss is less of a concern, leading to the conclusion that the most critical components for achieving mass and input power goals are the compressor and turbine components.

Fig. 6 considers the impact of the optimistic assumptions within the two-stage cryocooler concept and electrical network on the full aircraft system. The analysis was completed using the models generated within this paper as part of the DEAP investigation. The graph considers the effects of different levels of boundary layer ingestion expressed as a percentage of the height of the boundary layer over the aircraft fuselage along with the mass impact of the superconducting network. From this graph, it can be seen that a

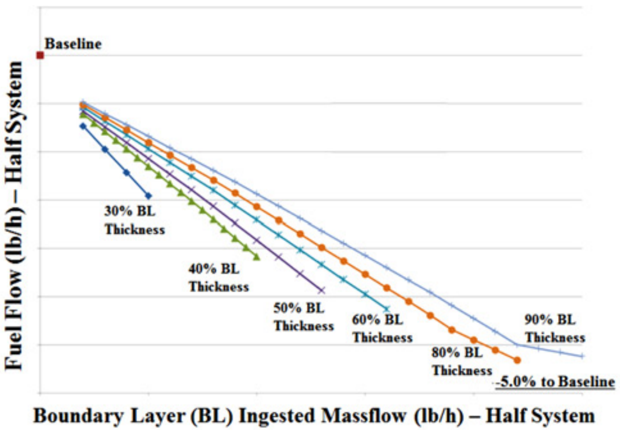

Fig. 6 *Cruise fuel burn reduction compared with baseline for DEAP concept for optimistic cryogenic and electrical system assumptions*

5% reduction in overall aircraft fuel flow can be achieved over the baseline aircraft. This highlights the importance of further detailed study of the cryogenics for future superconducting aircraft propulsion systems, particularly the development of high-efficiency components.

12 Conclusions and future work

This study has resulted in a number of key realisations when considering superconducting distributed propulsion for aviation. Chief among these is the importance of the cryogenic cooling system to any future concept, and the impact that system level design decisions and component-level performance has on the overall viability of the concept. Through systems level study and assessment of the requirements and functions, the critical functions were identified. This has resulted in the eventual selection of the RBCC as the most viable concept through qualitative means.

Numerical modelling of the RBCC has returned results that both validate the systems process critical functions and shown which components from a performance perspective are most critical. The RBCC concept design space has been better understood through this paper, with knowledge gained on what impacts certain high-level design choices will have on the as-of-yet undetermined final concept.

Furthermore, the most critical components have been highlighted as the compressor and turbine, where high sensitivity has been shown to exist in relation to the required level of technological advancement in the form of specific mass. A rudimentary but conceptually appropriate mass estimation method has been derived; however, further work must centre on increasing the fidelity of this mass estimation method.

Future system work must centre on numerical analysis of different heat exchanger types and for novel methods of compression where high compressive efficiencies are likely. Since the significant components in mass terms are likely to be the heat exchangers within RBCC concepts, additional mass within the compressor is likely to be acceptable should there be significant gains regarding the compressive efficiency. Further modelling work should centre on building robust tools that can be applied to different concepts such that rapid iteration of variables and enhanced design space mapping can occur. This rapid iteration capability has been achieved to an extent within this paper; however, significant future development is required in order to assess the impact on fuel burn of an aircraft concept and for whole-system integration. This will be crucial in the future understanding on how system level design choices for individual systems may not overall be optimum compared with the baseline.

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Due to commercial concerns, supporting data cannot be made openly available.

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Palmer, Joe

Institution of Engineering and Technology